Velocity field in the ICM: observational signatures and constraints

What do we do with near future high energy resolution data (Astro-H)?

I. Zhuravleva, E. Churazov, A. Kravtsov, R. Sunyaev

(Zhuravleva+11, to be subm.)
Direct velocity measurements

Perseus cluster today and tomorrow

Chandra

150 eV @ 6 keV

Astro-H

5 eV @ 6 keV
Observables

- Emissivity
- Shift of centroid
- Line width

Emissivity-weighted V and σ

σ(R) → structure function of turbulence
RMS(V)/σ → correlation length of velocity field
Observed $\sigma$ and structure function

$$SF(\Delta r) = \langle [V(r) - V(r + \Delta r)]^2 \rangle$$

At a given projected distance $R$ an interval $l_{\text{eff}} \sim R$ contributes to the line flux (and width)

Observed $\sigma(R) \propto \text{structure function } (l_{\text{eff}})$
Observed $\sigma$ and structure function

\[ SF(x) = 2 \int_{-\infty}^{+\infty} P_{1D}(k_z)(1 - \cos 2\pi k_z x) dk_z \]

\[ \sigma^2(R) = \int_{-\infty}^{+\infty} P_{1D}(k_z)(1 - P_{EM}) dk_z \]
Observed $\sigma$ and structure function

$\alpha = -\frac{11}{3}, k_m = 0.005$

Velocity dispersion

Structure function

$\beta = 0.6, r_e = 10$
RMS(V) and correlation length

\[ V_{3D} \]

\[ L < L_{\text{eff}} : \sigma \]

\[ L > L_{\text{eff}} : V_{2D} \]

\[ \text{RMS}(V)/\sigma - \text{proxy of correlation length} \]
RMS and spatial scales of motions

\[ \alpha = -\frac{11}{3}, k_m = 0.5 \]
\[ \alpha = -\frac{11}{3}, k_m = 0.05 \]
\[ \alpha = -\frac{11}{3}, k_m = 0.005 \]
\[ \alpha = -\frac{11}{3}, k_m = 0.0005 \]

\[ \beta = 0.6, r_c = 10 \]
Conclusions

Direct V measurements (Astro-H, 2014):

- Shift, width: velocity amplitude
- Width(R): structure function of turbulence
- RMS(shift)/width: correlation length of the velocity field
Perseus cluster: thermal broadening

Perseus cluster: $r < 500$ kpc
FeXXV line @ 6.7 keV
$V_{rms} = 500$ km/s
$V_{rms} = 370$ km/s
$V_{rms} = 250$ km/s
$V_{rms} = 200$ km/s
$V_{rms} = 150$ km/s
Resonant Scattering: NGC 5044

talk of Jelle de Plaa

Solid: isotropic
Dotted: radial
Resonant scattering

amplitude + anisotropy + correlation length

\[ R S \propto \tau \propto \frac{1}{\Delta E_D} \propto \left( \frac{V_{\text{therm}}^2 + V_{\text{turb}}^2}{1} \right)^{1/2} \]

(talk by Jelle de Plaa)

RS is mostly sensitive to:
- radial motions
- small scale motions

Zhuravleva+11a
Want to know
Amplitudes + spatial scales & anisotropy

Why?
Mass bias (e.g. Nagai+07, Lau+09)
ICM heating rate (e.g. Churazov+08)
Role in particle acceleration (e.g. Brunetti+06,11)

How?
Direct/Indirect measurements
<table>
<thead>
<tr>
<th><strong>Direct/Indirect measurements</strong></th>
<th><strong>XMM-Newton</strong></th>
<th><strong>Chandra</strong></th>
<th><strong>Astro-H (2014)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Width and shift of lines</strong></td>
<td>Weak upper limits on amplitudes (Sanders+11)</td>
<td>-</td>
<td>Amplitudes, spatial scales (Zhuravleva+11b)</td>
</tr>
<tr>
<td><strong>Resonant Scattering</strong></td>
<td>Upper limits on amplitude (e.g. Werner+09, Churazov+04) talk by Jelle de Plaa</td>
<td>-</td>
<td>Amplitudes, spatial scales, anisotropy (Zhuravleva+11a)</td>
</tr>
<tr>
<td><strong>Pressure fluctuations</strong></td>
<td>Spatial scales (Schuecker+04)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>SB fluctuations</strong></td>
<td>Spatial scales talk by E. Churazov</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Diffusion of heavy elements</strong></td>
<td>Amplitudes, spatial scales Rebusco+06</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

+ **X-ray polarization:** transverse gas motions (Zhuravleva+10)
+ **Kinetic SZ:** amplitudes
Resonant scattering: amplitude of motions

\[ \Delta E_D = E_0 \left[ \frac{2kT}{Am_p c^2} + \frac{V_{\text{turb}}^2}{c^2} \right]^{1/2} \]

\[ F_{\text{thin}} / F_{\text{thick}} \rightarrow V \]

Perseus cluster: \( V > 400 \text{ km/s at } r < 100 \text{ kpc} \) \((\text{Churazov+04})\)

NGC4636: \( V < 100 \text{ km/s in the core} \) \((\text{Werner+09})\)

NGC5044, NGC 5813 \((\text{talk by Jelle de Plaa})\)
Resonant Scattering: spatial scales and anisotropy

<table>
<thead>
<tr>
<th></th>
<th>Perseus, r&lt;10 kpc</th>
<th>Perseus, r&lt;30 kpc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropic</td>
<td>$V=500$ km/s</td>
<td>$V=500$ km/s</td>
</tr>
<tr>
<td>Radial</td>
<td>$V=200$ km/s</td>
<td>$V=300$ km/s</td>
</tr>
<tr>
<td>Tangential</td>
<td>$V=1500$ km/s</td>
<td>$V=1200$ km/s</td>
</tr>
</tbody>
</table>

Zhuravleva+11a
Resonant Scattering: spatial scales and anisotropy
Optical depth depends on the character of motions

RS is mostly sensitive to:
(1) radial motions
(2) small scale motions

Zhuravleva+11a
Resonant scattering: NGC4636

- No motions
- No RS
- Pressure support < 5% of the thermal $P$
- $V$ in the core < 100 km/s

Werner+09
Resonant scattering: NGC4636

\[ \Delta E_D = E_0 \left[ \frac{2kT}{Am_p c^2} + \frac{V_{turb}^2}{c^2} \right]^{1/2} \]

NGC4636

Wavelength, Å

RGS XMM Newton  0.5 arcmin

Observations: \( \frac{F_{17\text{Å}}}{F_{15\text{Å}}} = 2.04 \pm 0.21 \)

Prediction: \( \frac{F_{17\text{Å}}}{F_{15\text{Å}}} = 1.31 \)

Werner+ 09

\( F_{\text{thick}} \quad F_{\text{thin}} \quad V \)

thick: 8.8
thin: 0.5
Resonant scattering: Perseus

He-like Fe 6.7 keV line, optical depth \( \sim 3 \)

6.7 keV line is not suppressed \( \rightarrow V > 400 \) km/s

Churazov et al. 2004
Optical depth in X-ray lines

<table>
<thead>
<tr>
<th>Ion</th>
<th>$E$, keV</th>
<th>$f$</th>
<th>$\tau$, NGC 4636</th>
<th>$\tau$, Virgo/M87</th>
<th>$\tau$, Perseus</th>
</tr>
</thead>
<tbody>
<tr>
<td>O VIII</td>
<td>0.65</td>
<td>0.28</td>
<td>1.2</td>
<td>0.34</td>
<td>0.19</td>
</tr>
<tr>
<td>Fe XVII</td>
<td>0.83</td>
<td>2.73</td>
<td>8.8</td>
<td>0.0005</td>
<td>2.8 \times 10^{-8}</td>
</tr>
<tr>
<td>Fe XVIII</td>
<td>0.87</td>
<td>0.57</td>
<td>1.3</td>
<td>0.0007</td>
<td>1.5 \times 10^{-7}</td>
</tr>
<tr>
<td>Fe XXIII</td>
<td>1.129</td>
<td>0.43</td>
<td>0.016</td>
<td>1.03</td>
<td>0.16</td>
</tr>
<tr>
<td>Fe XXIV</td>
<td>1.168</td>
<td>0.245</td>
<td>0.002</td>
<td>1.12</td>
<td>0.73</td>
</tr>
<tr>
<td>Fe XXV</td>
<td>6.7</td>
<td>0.78</td>
<td>0.0002</td>
<td>1.44</td>
<td>2.77</td>
</tr>
</tbody>
</table>
Velocity field in SPH simulations: main problems

Numerical viscosity

Resolution

Simulations by Dolag et al. 2005
3D velocity power spectrum

Deviations from Kolmogorov PS
Dependence on considered volume
SPH and AMR show similar behaviour
Gas motions: observations

Broadening and shift of line: amplitude, dispersion

RGS XMM Newton: upper limits on V

(Sanders et al. 2010)
3D velocity power spectrum: resolution of simulations

\[ (P*4\pi k^3)^{1/2}, \text{km/s} \]

\[ k^{-2/3} \]

\[ k = 1/x, \text{kpc}^{-1} \]
A Mexican Hat with holes: a method to calculate low resolution PS from data with gaps

Arevalo et al. 2010 in prep.

\[ I_c(k) = \frac{G_{\sigma_1} * I}{G_{\sigma_1} * M} - \frac{G_{\sigma_2} * I}{G_{\sigma_2} * M} \]

i) \( I_c(k) \)

ii) variance of \( I_c(k) \)

trimming of boxes  
data with gaps
3D velocity power spectrum

SPH simulations by K. Dolag (Dolag et al. 2005), ~ 70·10^6 particles

g676 cluster: \( M_{\text{vir}} = 1.6 \cdot 10^{14} \) \( M_{\odot} \), \( R_{\text{vir}} = 1.43 \) Mpc

Does PS depend on considered volume of cluster?
Velocity field in the ICM: observational signatures and constraints

- anisotropy of velocity field
- correlation length of velocity field («spatial scales»)

I. Zhuravleva, E. Churazov, A. Kravtsov, S. Sazonov, R. Sunyaev, J. de Plaa, N. Werner, K. Dolag

Structure in Clusters and Groups of Galaxies in the Chandra Era, Boston 2011